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Deformation phases in the selected shear zones within the Tatra Mountains granitoid core

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Abstract: The paper presents the complex geological structure and microstructure of four selected polydeformed shear zones within the granitoid core of the High Tatra Mountains. Sequences of deformation and mineralization were determined for each zone. In order to determine the deformation conditions, petrotectonic analysis and the chlorite geothermometer were applied. The obtained data were correlated with earlier published fluid inclusions investigations. Next, the results were supported by petrotectonic and structural analyses, and on the basis of the whole set of data three groups of structures were distinguished: **1** — pre-Alpine (connected with late Variscan extension or Early Jurassic rifting, brittle-plastic in character); **2** — Alpine (formed during the Late Cretaceous thrusting, marked by the presence of flat-dipping slickensided faults); **3** — late Tertiary (linked with the uplift of the Tatra massif and the accompanying extension and sinistral oblique-normal-slip faults). On the basis of the pressure 1.45–1.70 kba (145–170 MPa) and temperatures (212–254 °C) estimated from fluid inclusion analysis, as well as temperatures range of 205–250 °C obtained from the Cathelineau geothermometer, the depth of the granitoid massif position during the Late Cretaceous Alpine thrust folding was determined at 6–7 km and the geothermal gradient at ca. 30 °C.

Key words: Western Carpathians, High Tatra Mountains, tectonic evolution, shear zones, granitoid rocks, cataclasites, mylonites.

Introduction

The Tatra Mountains represent the northernmost basement massif of the Inner Western Carpathians. The younger part of the crystalline core comprises granitoid rocks considered to be products of the Variscan Orogeny (Petrík et al. 1994). The isotopic ages of the granitoid intrusion of the Tatra Mountains range between 300–330 Ma according to the $^{40}Ar/^{39}Ar$ and Rb/Sr methods (Burchart 1968; Maluski et al. 1993; Janák 1994; Kohút & Sherlock 2003) and 340–310 Ma according to zircon dating (Poller et al. 2000; Poller & Todd 2000). The depth of the magma intrusion was estimated at 18–22 km, which corresponds to 5–6 kbar (500–600 MPa) and 450–550 °C (Kohút & Janák 1994). During the Variscan Orogeny, the first deformation stage is related to the south-eastward ductile thrusting of the upper unit composed of granites and migmatites over the footwall metasediments of the Western Tatra Mountains (Fritz et al. 1992; Janák 1994). The second Variscan extensional deformation was characterized by W-E stretching (Kohút & Janák 1994). After the Permian, the Tatric pre-Alpine complexes were buried not deeper than 12 km (ca. 250 °C — Kováč et al. 1994). Structural studies of Putiš (1992), Kohút & Janák (1996) and Janák & Kahan (1996) suggest the brittle character of the deformation during the Alpine stage occurring in low P-T conditions. The Tertiary uplift of the Tatra Mountains took place 15–10 Ma ago, as shown by apatite fission track dating (Burchart 1972; Kráľ 1977; Kováč et al. 1994).

This paper is focused on the presentation of selected shear zones within the High Tatra Mountains granitoid core (Fig. 1A) in relation to their multistage tectonic evolution documented by several phases of deformation and mineralization. Despite the polydeformed character of these zones, it is possible to determine the chronology of events, conditions of deformation in each stage of tectonic evolution, as well as to relate them to regional events.

Classification of shear zones

The granitoid core of the High Tatra Mountains is cut by several-meters thick tectonic zones, clearly visible in the morphology as cols. According to Grochocka-Piotrowska (1970) these zones can be subdivided into:

a — so-called "uniform slip zones", comprising numerous slickensides with closely adherent fault-walls;

b — "debris zones" — cataclasites, mylonites and tectonic breccia;

c — fault zones with ductile deformation.

Jurewicz (2000a, 2002) presented a slightly different view for distinguishing particular dislocations within the granitoid core of the High Tatra Mountains, based on their geometry. The dislocations were initially sub-divided into two groups: flat-dipping faults with dips <45° (Fig. 1D) and steep singular faults and faults zones (Fig. 1C,E) with dips >45°. The flat-dipping faults are characterized by most commonly 20–80°

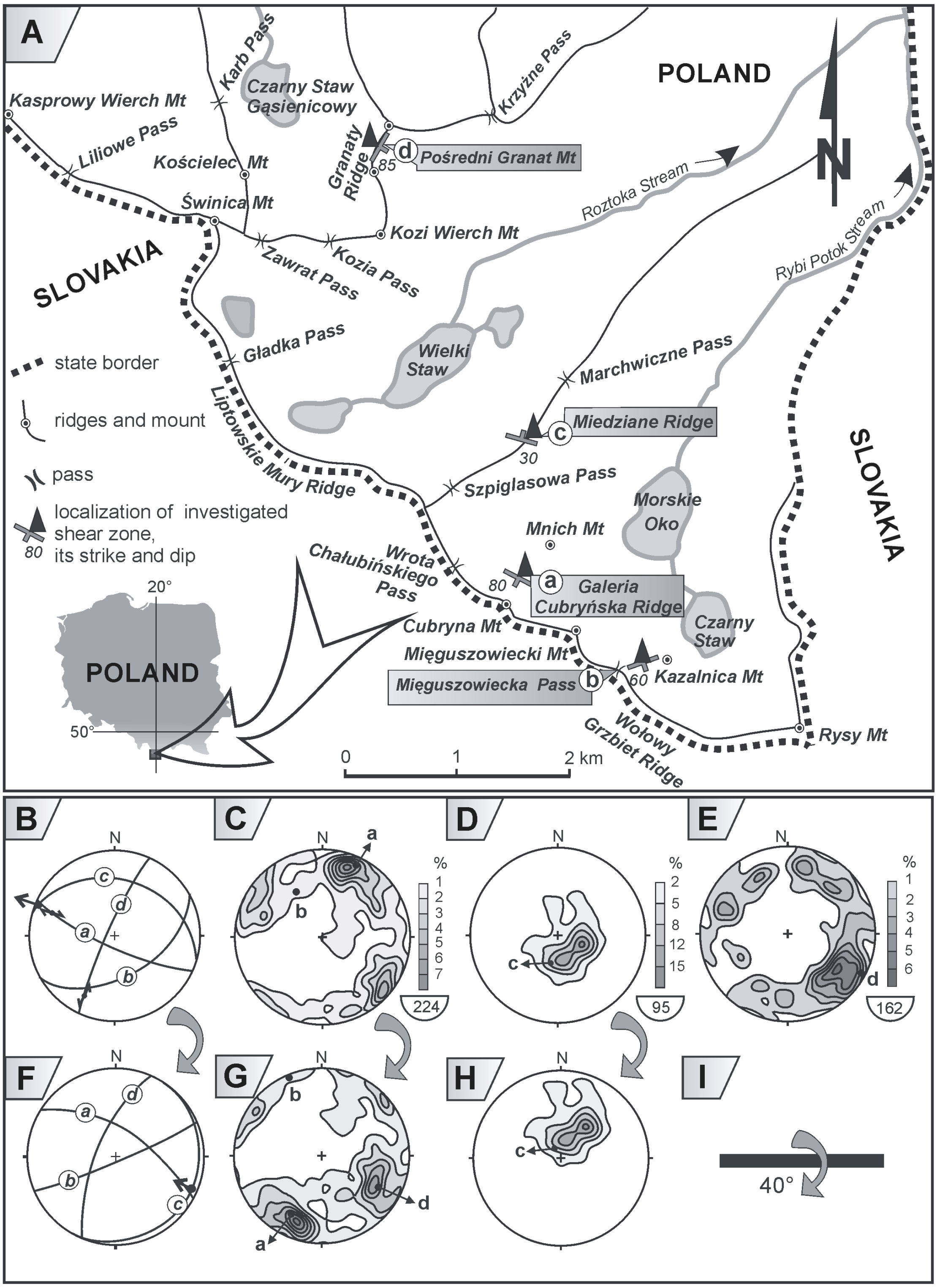

Fig. 1. A — Sketch-map of the Polish part of the High Tatra Mountains and location of the four studied mylonitic zones: a — Galeria Cubryńska Ridge; b — Mięguszowiecka Pass; c — Miedziane Ridge; d — Pośredni Granat Mountain. **B–H** — stereoplot of the shear zones, projection on the lower hemisphere: B — orientation of the investigated shear planes; arrow points orientation of striae; C — pole to the (a) and (b) shear planes in relation to the contour plot of the pre-Alpine mylonitic zones; D — pole to the (c) shear plane in relation to the contour plot of the flat dipping fault planes of Alpine ages; E — pole to the (d) shear plane in relation to the contour plot of the steep-dipping shear zones (normal-oblique-slip faults) of late Tertiary age; F,G,H — after rotation of the Tatra Mountains block to the position prior to the late Tertiary rotational uplift (40° southwards around the 90/0 axis; see for detail: Jurewicz 2000a, 2002); Note that the orientation of the *d*-plane after rotation (F, G) and without rotation is correlated with the maximum of steep faults (E) connected with Neogene extension. **I** — scheme of rotation along horizontal axis to position prior to the late Tertiary uplift.

oriented, smooth planes and the presence of tectonic striations on mineralized surfaces (most commonly epidote-quartz or chlorite-quartz). They are linked with the Alpine thrust folding, and the striae allowed reconstruction of the stress field responsible for the thrust formation in the Tatra Mountains (Jurewicz 2000a,b). Steep faults, in turn, do not comprise a uniform group in relation to their orientation, character of accompanying structures, as well as their origin and age. In Jurewicz (2002) they were tentatively sub-divided into:

a — steep dislocations comprising mylonites and/or cataclasites, several tens of cm to approximately 2–3 m wide, or comprising a series of narrow zones from several to several tens of cm wide, with strikes about 40° or 110° (Fig. 1C);

b — steep dislocations comprising singular planes or systems of several parallel planes with strikes about 35° (Fig. 1E).

The geometric analysis of singular steep fault planes allowed us to identify them as sinistral strike-slip faults or oblique-normal-slip faults, and to link them with the Middle Miocene 106–120° (Jurewicz 2002) extension, which took place after the rotational uplift of the Tatra Mountains (Piotrowski 1978; Kováč et al. 1994; Sperner 1996; Żelaźniewicz 1996; Jurewicz 2000a). Dislocations comprising cataclasites and mylonites are most probably older that the flat-dipping slickensides, as well as the steep singular slickenside fault planes. However, dislocations with orientations similar to those of steep faults could be reactivated during the late Tertiary uplift of the Tatra massif. Some of the fault planes could be geometrically connected with magmatic-tectonic jointing described by Jaroszewski (1985). During the Alpine thrust movements the presently steep dislocation zones did not lie in orientations close to the planes of maximum shearing, therefore they were not reactivated.

In the Polish part of the High Tatra Mountains, low dips of the cataclastic and mylonitic zones are rather uncommon. One such zone was identified in the vicinity of Czarna Ławka in Liptowskie Mury, where it is ca. 40 cm thick and is oriented at 340/35; the second one described below occurs on the Miedziane Ridge, where ca. 10–20 cm thick mylonitic epidote occurs.

Methodology

Observations of structures and textures were carried out directly in the field, on polished surfaces, in an optical microscope and a microprobe (BSE images). The minerals were recognized under an optical microscope, and the chemical composition was determined by microprobe analysis. To determine the temperature conditions of the deformation and mineralization processes, the chlorite geothermometers (Cathelineau & Nieva 1985; Cathelineau 1988) were applied.

There is a certain problem in contemporary literature with the precise application of the terms "mylonites" and "cataclasites". The existing criteria are not clear. Some authors when describing rocks from shear zones use the term "tectonites". Cataclastic zones are difficult to distinguish from mylonitic zones in the field. Cataclasites are considered to be rocks comprising sharp-edged rock and mineral fragments, crushed during the process of brittle fracturing, however without melting (Passchier & Trouw 1997). Mylonites are defined as strongly deformed rocks occurring in ductile shear zones, commonly with planar foliation and stretching lineation (Passchier & Trouw 1997; Bucher & Frey 2002). Lapworth (1885) linked mylonites with brittle faults; presently, however, they are considered to be formed under the influence of crystal-plastic matrix flow, despite the fact that brittle deformation is observed in isolated rock lenses and individual mineral grains (some minerals reveal brittle fractures). According to Yardley (1991) the presence of neoformed minerals is a prerequisite to assign rocks from shear zones to mylonites.

The internal fabric of mylonitic zones in the Tatra Mountains differs in the degree of the mylonitization process and number of deformation and mineralization phases. The variation of the mylonitic structures is also observed within particular zones and is linked with the degree of structural reworking changing along each zone. The zones reveal traces of reactivation, for example, in the form of deformation of mylonitic fabrics formed during earlier shearing, or mineral veins formed during progressive deformation and in relaxation stages. This paper shows the complex and variable structure of the shear zones in the Tatra Mountains and the poly-phase process leading to their formation based on selected dislocation zones: in the Galeria Cubryńska Ridge, on Pośredni Granat in the Granaty Ridge, in the Mięguszowiecka Przełęcz pod Chłopkiem Pass, further referred to as the Mięguszowiecka Pass, as well as on the Miedziane Ridge (Fig. 1A). On the basis of the succession and condition of deformation, the phases of development were correlated with stages of tectonic evolution of the High Tatra Mountains.

Characteristics of the selected shear zones

Galeria Cubryńska Ridge

This 205/80 oriented zone (Fig. 1A,B-*a*,C-*a*) transects the north-western slopes of the Cubryna Mountain — the so-called Galeria Cubryńska, and is one of the widest and most complex zones in the series of three parallel tectonic zones in this area. It is ca. 1.5–2 m wide and represents a fissure cutting several tens of meters into the massif, with a clearly-visible debris fan beneath it. After reversing to the position prior to the post-Paleogene rotational uplift this zone attains the dip of ca. 75° (Fig. 1F-*a*,G-*a*). Its internal structure is very complex. It is delimited from the wall rocks (Fig. 2A-*1*) by distinct slickenside surfaces (Fig. 2A-*5*) coated with ca. 0.5–2 cm thick mylonitic epidote with clear 292/35 shear striae indicating a dextral dip-slip movement. The slickensides document the last phase of movement, which took place along the boundary of rock media with different reological properties (mylonite and granitoid). The filling of fractures (quartz-filled gashes — Fig. 2A-*6*) with orientations parallel to the margins of the mylonitic zone and developed along the boundary of the earlier vein of green quartz (Fig. 2A-*4*) are younger than the movement phase. The quartz vughs developed along the northern margin of the mylonitic zone, probably grew in an extensional fissure but did not fill it entirely; the space between the crystals is filled with younger white milky calcite

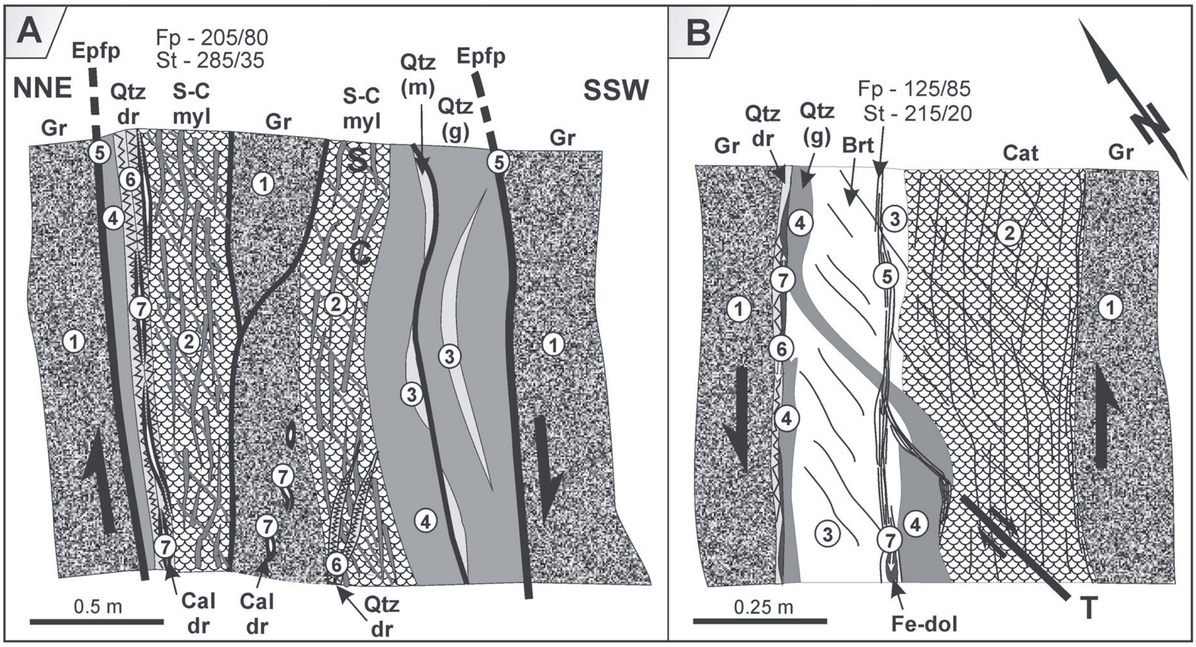

Fig. 2. Sketch of the shear zones of the Galeria Cubryńska Ridge. **A** — view from the south, and the Pośredni Granat Mountain. **B** — view from above. Numbers indicate the order of the deformation and mineralization phases: **1** — granitiod wall rock, **2** — zone of mylonitization, dynamic recrystallization and texture reworking, **3** — veins filled with milky quartz and barite, **4** — veins filled with green quartz, **5** — slickenside surfaces coated with mylonitic epidote, **6** — quartz-filled gashes, **7** — younger milky calcite druses and Fe dolomite. **Gr** — granitoid, **S-Cmyl** — S-C mylonites, **S** — foliation, **C** — shear surface, **Cat** — cataclasites, **Qtz** — quartz, **m** — milky, **g** — green, **dr** — druse, **Cal** — calcite, **Ep** — epidote, **Brt** — barite, **Fp** — fault plane, **St** — striae, **Fe-dol** — ferrous dolomite, **T** — tension fractures of Riedel-type shear system, filled with quartz, with later antithetic movement.

(Fig. 2A-*7*). Calcite in this zone also occurs in lens-shaped druses within the moderately deformed granitoid (Fig. 3A). This calcite, as well as other carbonates in other places has a characteristic ferricrust. Earlier than the green quartz (Fig. 2A-*4*), the colour of which comes from chlorite, are veins of milky quartz (Fig. 2A-*3*), which underwent boudinage and slight deformation. The oldest tectonic phase is linked with a shear process, which resulted in mylonitization, dynamic recrystallization and textural reworking (Fig. 2A-*2*). The effects of this process can be seen directly in the field in the form of the S-C structures indicating the downward displacement of the southern limb. The S-surfaces are wavy-shaped foliations cut by the C-planes surfaces defined by microshears parallel to the shear-zone boundary (see Shimamoto 1989; Lin 1999). Porphyroclasts of magmatic quartz, several-mm in diameter, which bear traces of brittle deformation (cataclastic fracturing), can be observed on a polished surface (Fig. 3C). Under the microscope the quartz porphyroclasts show undulose extinction and fabrics of dynamic recrystallization.

The S-C fabrics have also been recognized under the microscope (Fig. 4A). Along the S-C surfaces elongated grains of neoformed quartz in the pattern of an anastomosing network occur. This quartz is also characterized by undulose extinction. According to Lin (1999) one of the most significant microstructural differences between the S-C cohesive cataclasites and the S-C mylonites is the absence of dynamically recrystallized grains in S-C cataclasites, what unequivocally points to the Galeria Cubryńska shear zone as mylonites. The rock has a green colour from chlorites developed after primary biotite, the presence of which has been registered under the microscope as well as in BSE images (Fig. 5A). Undulose extinction, deformation bands and kink bands are clearly visible in plagioclase porphyroclasts (Fig. 4D), pointing to the low-grade condition of deformation taking place typically in temperatures 300–400 °C (Pryer 1993; Passchier & Trouw 1996). Furthermore, internal fracturing, occasionally filled by epidote and quartz (Fig. 4E) also occurs. Nucleation and growth of new minerals such as white mica porphyroblasts overgrowing sericite-rich matrix is also observed in the thin section (Fig. 4B). Later than the newly grown mica flakes are veins of calcite fibres (Fig. 4C).

Fluid inclusions analyses from the milky quartz vein (Jurewicz & Kozłowski 2003) point to the temperature 264 °C and pressure 1.6 kbar (160 MPa), and the observation of the deformation character indicate that the temperature could reach beyond 300 °C. The data, obtained in studies of fluid inclusions from vein quartz in other mylonitic zones indicate the pressures of ca. 1.3–1.63 kbar (130–160 MPa) and temperature of ca. 264–316 °C (Kozłowski & Jurewicz 2001; Jurewicz & Kozłowski 2003). For neomorphic quartz from shear surfaces in mylonites the respective values obtained by Kozłowski are: 1.3 kbar (130 MPa) and 216 °C (in Kornatowski 2002).

Mięguszowiecka Pass

This is one of the several almost parallel mylonitic zones occurring in the vicinity of the Kocioł Mięguszowiecki cirque.

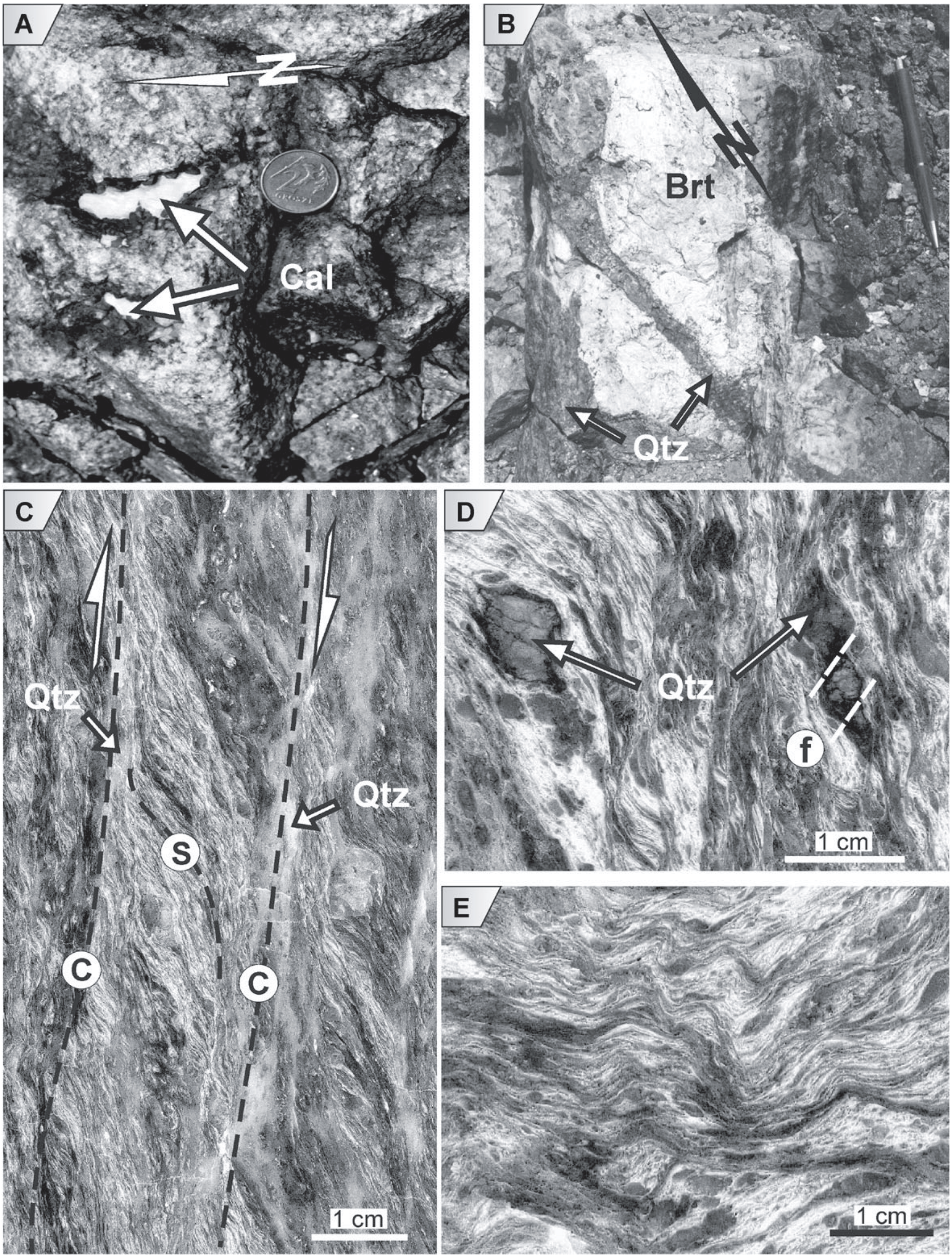

Fig. 3. A — calcite druse with core of iron oxides and hydroxides, Galeria Cubryńska Ridge (correlated with *7* on Fig. 2A). **B** — vein of quartz (dark) transecting a barite vein (light), Pośredni Granat Mountain (view from above; details on the Fig. 2B). **C–E** — polished surfaces: C — S-C mylonites from Galeria Cubryńska Ridge with the neoformed quartz along the shear bands; D — microfaults (f) transecting porphyroclasts of quartz; relicts of S-C fabrics, Mięguszowiecka Pass; E — asymmetric microfolds of mylonitic foliation with elongated and boudinaged porphyroclasts of quartz, Mięguszowiecka Pass.

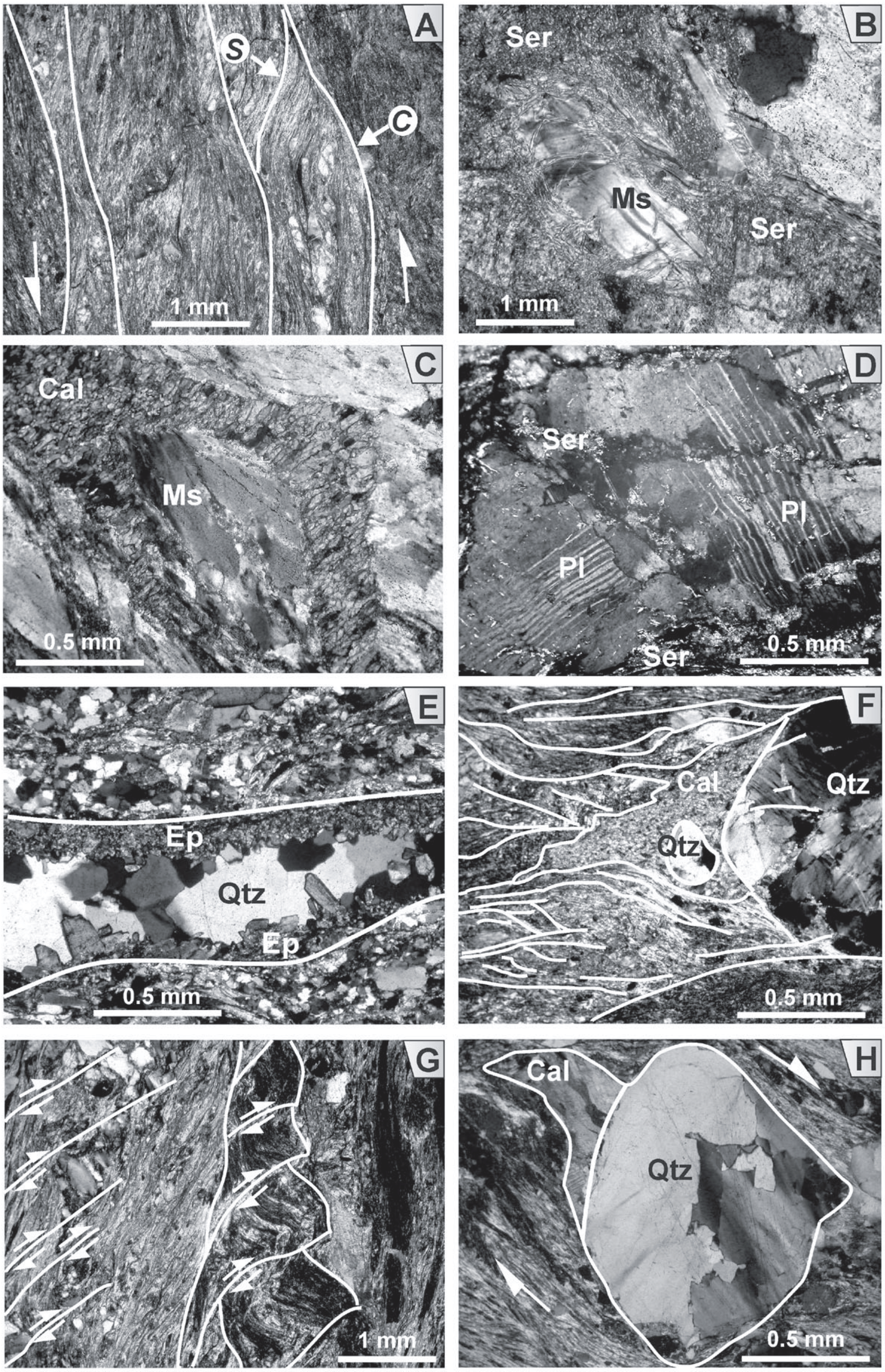

Fig. 4. Thin sections in crossed polarizers: A–E — Galeria Cubryńska Ridge, F–H — Mięguszowiecka Pass. **A** — polymineralic foliation composed of quartz/mica/sericite/feldspar layers in S-C mylonites; arrows indicate sense of shear. **B** — nucleation of mica porphyroblast grown on sericite. **C** — veins of calcite fibres between mica flakes. **D** — deformation of twins in plagioclase. **E** — vein (rims marked white) of euhedral epidote grown along the vein-wall, filled with quartz. **F** — porphyroclast of quartz with fine-grained calcite in strain shadows; quartz crystal shows deformation lamellae and undulose extinction; tension gashes filled with calcite. **G** — microshears associated with microfolds; arrows indicate sense of shear. **H** — porphyroclasts of quartz with elongated crystals of calcite in strain shadows; arrows indicate sense of shear.

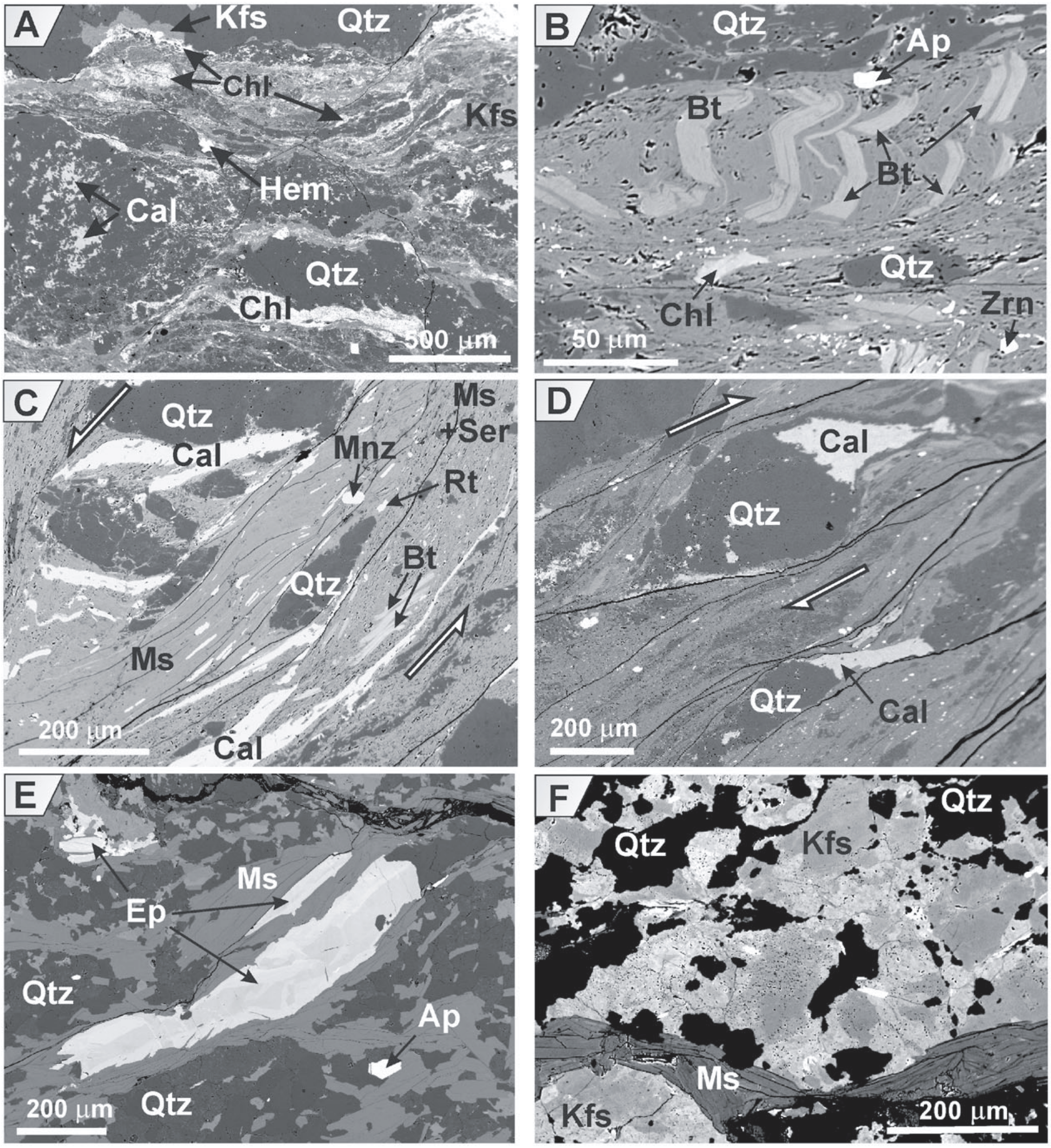

Fig. 5. BSE-images: A–B — Galeria Cubryńska; C,D,E — Mięguszowiecka Pass; F — Miedziane Ridge. **A** — metamorphic and neomorphic minerals and mylonitic fabrics. **B** — ductile folded, kinked and disrupted crystals of Ti-rich biotite. **C** — rotated porphyroclast of fractured quartz with calcite in strain shadows; intercrystalline slip within mica-bar porphyroclast (like mica "fish" structure). **D** — calcite in strain shadows adjacent to quartz porphyroclast, partially newly recrystallized (σ-type object); note undulose extinction and brittle fractures filled with calcite in the quartz porphyroclast. **E** — bright parts of epidote blast (Fe-rich) grown on darker (Fe-poor), earlier formed and crushed ones. **F** — zoned K-feldspar with Ba-rich rims (the bright parts of the feldspars); arrows indicate sense of shear; symbol of minerals after Kretz (1983).

This zone (Fig. 1A,B-*b*,C-*b*), ca. 1–2 m wide and oriented 150/60, cuts the massif of Mięguszowiecki Szczyt Czarny Mountain on its northern slope. After reversing to the position prior to the post-Paleogene rotational uplift this zone attains a sub-vertical position (Fig. 1F-*b*,G-*b*). Due to the fact that it is well exposed for a distance of ca. 300 m, from Kazalnica to the Mięguszowiecka Pass, the variation of microstructures and deformation gradient can be observed along its strike. In the lower, more eastern parts in the vicinity of Kazalnica, characteristic deformation textures such as folding (Fig. 3E) and microfaulting (Fig. 3D) of pre-existing foliation can be observed. The folds within this zone are not indicators of the shear sense, because fold axial planes do not show specific orientation and can have the same or the opposite sense of asymmetry to the bulk displacement. This fact may be linked with the back rotation between the shear zone during progressive deformation (see Harris 2003) or change in the direction of movement (Hippertt & Tohver 1999). Brittle deformation (Fig. 3D), that is cataclastic fracturing, shearing of grains showing "domino"-like microstructures can be observed in porphyroclasts of magmatic quartz (see Needham 1995; Hippert & Hong 1998). Strain shadows usually composed of calcite or neoformed SiO_2 may occur adjacent to quartz porphyroclasts (Figs. 4F,H, 5C,D). Closer to the Mięguszowiecka Pass the shear zone is filled with tectonic gouge. It is likely that the minor folding of mylonitic fabric is linked with the older deformation phase, whereas the tectonic gouge and uncohesive cataclasites developed in a later deformation phase due to the reactivation of an existing mylonitic zone. There are also fragments of crushed and deformed quartz veins in some parts of the mylonitic zone. Analyses of fluid inclusions made by Kozłowski (in Kornatowski 2002) indicated temperatures of 262 °C and pressures of 1.6 kbar (160 MPa), which are values similar to those obtained for the Galeria Cubryńska Ridge. In the younger quartz veins developed along the walls of the mylonitic zone, euhedral grains are observed, with spaces between them filled with later ferrous carbonates (Fe-dolomite and ankerite). These carbonates are typically poorly preserved and empty voids with walls built of quartz crystals coated with Fe-hydroxides, being the remains after weathering of Fe-rich carbonates, are often observed. According to Michalík (1952), carbonate veins in granitoids of the High Tatra Mountains reveal a zonal composition: the middle part consists of calcite, whereas dolomite, followed by ankerite and siderite occur towards the margins. The variability within the mineral composition is observed in single dolomite crystals, which also have a zonal composition, where their rim is composed of ankerite (Kornatowski 2002). Such composition of the carbonate veins may be a result of Fe-ions migration and their gradual disappearance from hydrothermal solutions, which in the terminal phase contained "pure" calcite.

In the vicinity of the Kocioł Mięguszowiecki cirque lie several parallel mylonitic zones, which are linked with the presence of the so-called violet, or titanous-violet veins (Jaczynowska 1980) of controversial origin. Their first chemical analysis was presented by Kreutz (1924), whereas their origin was given by Koisar & Zawidzki (1972). The authors determined the geochemical transformations taking place in mylonitic zones leading to the increase of hematite contents responsible for the specific colour of the veins. By analogy to the site from Gerlach described by Petrík & Reichwalder (1996; see also Petrík et al. 2003 and Kohút & Sherlock 2003), Gawęda & Piwkowski (2000) considered the violet veins from Kończysta Turnia Mountain, and Pasternakowe Czuby Mountain as pseudotachilites, also postulating a similar origin for the violet veins in the entire Tatra Mountains, including those from Kocioł Mięguszowiecki cirque. We suggest that violet veins from the vicinity of Kocioł Mięguszowiecki cirque and the role of hematite and titanite require a separate analysis.

Miedziane Ridge

On the Miedziane Ridge running towards the Marchwiczna Pass (Fig. 1A) a flat-dipping, smooth tectonic surface, oriented 15/35, can be observed (Fig. 1B-*c*,D-*c*). The shear plane is coated with mylonitic epidote and slickensided. The striae are semiparallel to the strike of the plane (Fig. 1B-*c*). The orientation and character of this surface does not match the described above mylonitic zones (Fig. 1B-*c*,D-*c*). It shows a geometric coincidence with the sloping slickensides linked with Alpine thrusting (Burchart 1963; Jurewicz 2000a). After rotation of the fault plane to the position prior to the late Tertiary uplift of the Tatra massif it attains a near horizontal position (Fig. 1F-*c*, H-*c*). It differs from other similarly oriented planes by the presence of a ca. 15-cm-thick mylonitic epidote-quartz mass, occurring instead of a thin, typically not exceeding ca. 2 cm mineralization comprising of synkinematicaly grown epidote and quartz. SEM photographs of epidote (Fig. 5E) show a clear mosaic-like composition of that mineral (angular shape of previously mylonitized grains). This could be a result of multiple activity of this shear zone where crystals were crushed and then recrystallized.

The composition of some minerals found in the Miedziane Ridge and Mięguszowiecka Pass shear zones are presented in Table 1. Their position in the rock texture is shown on Fig. 5E,F. The high Ba contents in K-feldspar, characteristic of such conditions and the zonation in epidote, which indicates the decrease in temperature during mineral crystallization is notable (see higher Fe contents in the rim area than in the previously grown and crushed blasts on Fig. 5E — with higher Fe content the colour of the epidote crystal is brighter).

The results of fluid inclusion investigations from the epidote-quartz assemblage on similarly oriented slickenside fault-planes indicated the temperature interval from 212 to 254 °C and pressures ranging from 1.45 to 1.73 kbar (145–173 MPa) (Jurewicz & Kozłowski 2003).

Pośredni Granat Mountain–Granaty Ridge

The tectonic zone occurring in the Granaty Ridge (Fig. 1A) is unique due to the fact that it transects the peak of Pośredni Granat Mountain (2235 m), and does not — as usually — form a pass. The reason for such preferential erosion is the presence of the largest barite vein in the entire Tatra Mountains (Figs. 2B, 3B). Besides the Granaty area, barite in lens-like form was found in the couloir below the Rohatka Pass in the Polski Grzebień massif (Paulo 1997). The 20-cm-thick barite vein from Pośredni Granat Mountain (Figs. 2B-*3*, 3B) occurs within a ca. 1–1.5 m thick cataclastic zone oriented 305/85 (Figs. 1B-*d*,E-*d*, 2B-*2*). It is relatively older than the vein of green quartz (Fig. 2B-*4*), which fills the space between the barite and the wall rock, cuts the barite vein along a tension fracture (T-type of the Riedel shear zone) and runs to its other side. Younger than the barite, and the quartz mineralization, is the several-cm-thick shear zone running inside the barite vein (Fig. 2B-*5*). During shearing and quartz mineralization the remobilization of barite took place (Fig. 2-*5,6*). Under the microscope this area is reflected by the co-occurrence of fine-grained barite and quartz filling the spaces between large crystals of tabular habit. Translations along the earlier originated tension fractures (T-type), with the opposite sense with respect to the shear zone of the Pośredni Granat Mountain are connected with the next stage of tectonic activity (see Ahlgren 2001).

At the boundary between the barite vein and the wall rock beyond the shear zone the break off took place in further stages. The resulting space was subsequently filled with quartz

Table 1: Composition of the main minerals occurring in selected shear zones from the Tatra Mountains.

	Miedziane Ridge				Męguszowiecka Pass				
	Epidote[1]	Epidote[1]	K-feldspar[2]	K-feldspar[2]	Chlorite[3]	Chlorite[3]	Chlorite[3]	Muscovite/ Sericite[4]	Muscovite/ Sericite[4]
SiO_2	37.90	37.48	64.57	63.36	30.02	27.74	30.86	45.36	45.41
TiO_2		0.13			0.44	0.49	1.30	0.93	0.85
Al_2O_3	25.81	21.86	18.72	18.59	23.79	20.70	20.25	31.57	31.95
Fe_2O_3	10.26	15.65							
Mn_2O_3	0.30	0.19			0.07	0.06	0.10	0.00	0.00
FeO					19.34	23.48	20.17	4.60	4.33
MgO					13.47	15.55	14.60	0.97	0.89
CaO	23.26	22.68			0.01	0.00	0.03	0.02	0.00
BaO			0.35	1.24					
Na_2O			0.67	0.24	0.04	0.02	0.03	0.30	0.31
K_2O			15.67	15.71	1.72	0.16	0.79	10.61	10.64
H_2O+	1.85	1.80			12.01	11.63	11.88	4.37	4.38
Total	99.38	99.80	99.97	99.14	100.91	99.83	99.99	98.71	98.75
Si	3.00	3.01	2.99	2.98	6.05	5.73	6.26	6.23	6.22
Ti		0.01			0.07	0.08	0.20	0.10	0.09
Al	2.40	2.07	1.02	1.03	5.65	5.03	4.84	5.11	5.16
Fe^{3+}tot	0.61	0.94							
Mn^{3+}	0.01	0.01			0.01	0.01	0.01	0.00	0.00
Fe^{2+}					3.26	4.05	3.42	0.53	0.50
Mg					4.03	4.78	4.41	0.20	0.18
Ca	1.97	1.95						0.00	0.00
Ba			0.01	0.02					
Na			0.06	0.02	0.44	0.04	0.20	0.08	0.08
K			0.92	0.94	0.02	0.01	0.01	1.86	1.86
Total	7.99	7.98	5.00	4.99	19.52	19.73	19.34	14.09	14.08
$Al+Fe^{3+}$tot	3.02	3.02		Al^{IV} in chlorite	0.98	1.14	0.87		
pie	0.29	0.19		T (°C)	253.00	304.00	219.00		
pist	20.18	31.31							
zo	79.52	68.50							

[1] — all Fe computed as Fe^{3+}, analyses normalized to 12O+OH. [2] — analyses normalized to 8O. [3] — all Fe computed as Fe^{2+}, analyses normalized to 20O+16OH. [4] — all Fe computed as Fe^{2+}, analyses normalized to 20O+4OH. Temperatures calculation according to Cathelineau & Nieva (1985) and Cathelineau (1988).

(Fig. 2B-*6*). On the boundary between the quartz and the barite vein as well as along the shear zone lenses of later Fe-carbonate mineralization occur (Fig. 2B–*7*). Along this zone barite attains a pink colour, which according to Paulo (1997) is linked with dispersed hematite pigment.

The green quartz vein was investigated using inclusion analyses (Jurewicz & Kozłowski 2003), which indicated the crystallization temperature of 210 °C and pressure of 0.85 kbar (85 MPa). This pressure value is much lower than that obtained from quartz in other shear zones of the High Tatra Mountains area and can be correlated with extension connected with the late Tertiary uplift of the Tatra Mountains (Kováč et al. 1994; Birkenmajer 1999). The orientation of this zone (Fig. 1B-*d*,E-*d*) also allows us to link this zone with other steep dislocations (oblique-normal-slip faults) connected with Miocene extension (Jurewicz 2002).

Discussion and conclusions

The structural analysis of the selected shear zones in connection with the determination of the deformation microstructures and chronology of events allowed a tentative correlation with stages of the Tatra Mountains tectonic evolution presented in Fig. 6. Three groups of structures can be distinguished corresponding to three distinct tectonic stages:

1 — The pre-Alpine stage *sensu lato*, with relicts of structures linked with the late Variscan extension distinguished by Kohút & Janák (1994), as well as those developed during the Early Jurassic rifting of the Variscan continental crust (Plašienka 1991, 2003a; Plašienka & Prokešová 1996). Deformation in these zones is of brittle-plastic character. The dips of their planes (Fig. 1C), with regard to the late Tertiary rotation (Fig. 1F,I) are steep (ca. 60°) and thus typical rather for normal faults than for flat-dipping thrusts (Davis & Reynolds 1996), whereas the sense of movement determined in the Galeria Cubryńska Ridge on the basis of the S-C fabrics indicates a reverse fault, which testifies to its multiple reactivation. Zones of this type were also reactivated in presence of the Neogene stress field as sinistral normal-oblique-slip faults, which resulted in striations on the slickensided, epidote-coated wallrocks.

2 — The Alpine stage is linked with horizontal NW and N compression and the resulting thrusting and folding, which are marked in the granitoid massif by the presence of flat-dipping thrust-faults with smooth slickensided surfaces coated with

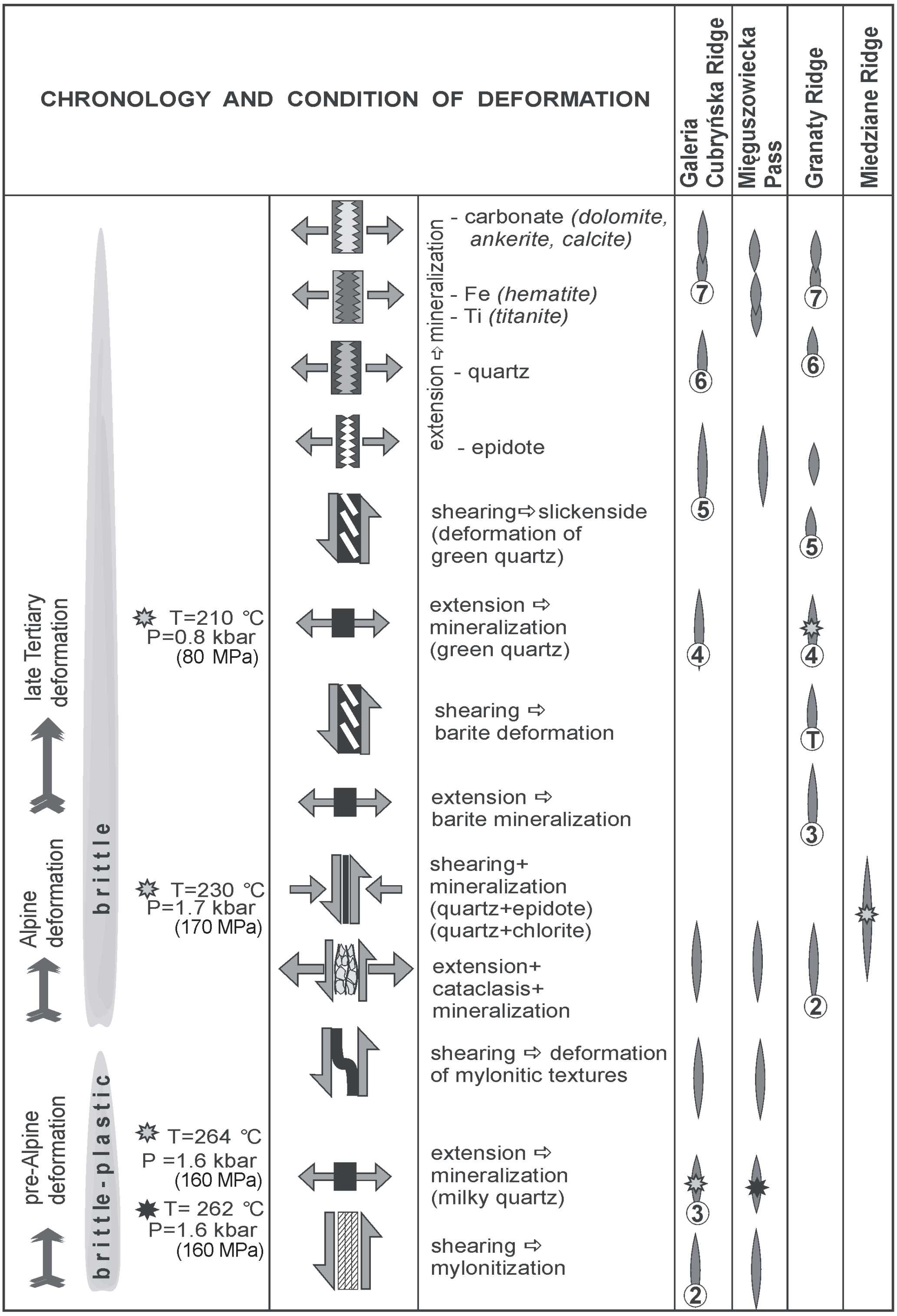

Fig. 6. Chronology and condition of deformation within the selected shear zones. Numbers in the circles correspond to Fig. 2.

quartz and epidote (Fig. 1D). The primary dips of these planes obtained from rotation (Fig. 1I) to positions prior to the Neogene uplift were southwards (Fig. 1H). These faults do not bear traces of activation during younger tectonic phases.

3 — The late Tertiary stage is linked with the uplift of the Tatra block and the accompanying extension and sinistral oblique-normal-slip faults. During this stage several new normal faults were formed and the reactivation of older mylonitic zones took place, where break off along the walls and an oblique-slip movement took place. These faults were formed in the present position of the Tatra block and do not require rotation. The convergence of the orientation of some mylonitic zones in the present position of the Tatra block (Fig. 1C) with the position of faults developed in the late Tertiary (Fig. 1E), which led to the reactivation of older zones, is observed.

The particular tectonic stages were best registered in the shear zone on Galeria Cubryńska Ridge (Figs. 2, 6), whereas the Mięguszowiecka Pass mylonitic zone — although similar in the deformation character — underwent reactivation in brittle conditions in later tectonic stages, which led to the complete destruction of older structures and the formation of loose cataclasites and tectonic gouge. The reactivation process took place in the late Tertiary during the uplift of the Tatra block (Burchart 1972; Kováč et al. 1994), when the existing discontinuity plane was reactivated. According to Sibson (1977) and Lin (1999) incohesive cataclasites are generally produced at shallow depths (<4 km), whereas mylonites may be formed at depths of 7–15 km in the brittle-ductile transition zone of predominantly crystal-plastic deformation. Guermani & Pennacchioni's (1998) observations in the Mont Blanc massif suggest that mylonites progressively develop by the plastic reactivation of cataclastic shear zones during greenschist facies metamorphic conditions. Thus, plastic deformation appears as second in brittle discontinuities with fine-grained matrix of cataclasites, which suggests that depth is not a factor necessary for the development of mylonites. In the case of the Mięguszowiecka Pass a reverse process can be observed: ductile deformation underwent brittle destruction (mylonites overprinted by brittle fracturing, see Scholz 1988) in a younger tectonic phase.

On the basis of the values of temperature and pressure obtained from fluid inclusion study and from observations of the deformation microstructures, the conditions, in which tectonic zones were developed in a particular stage, can be compared. The data obtained from the fluid inclusions studies proved that synkinematic quartz slickenfibres on fault surfaces (connected with Alpine thrusting) crystallized at higher pressure and lower temperature (1.45–1.7 kbar (145–170 MPa), 212–254 °C) than vein quartz in mylonitic zones (1.3–1.63 kbar (130–163 MPa), 264–316 °C). The pressure values 1.45–1.7 kbar (145–170 MPa) for structures linked with Alpine thrusting allows us to estimate the depth of the deformation processes at 6–7 km. Higher pressure values for flat-dipping fault-thrusts may be a result of horizontal compression exceeding the values of lithostatic pressure as well as of loading by the thrusting nappe units, whereas the lower values of pressure for mylonitic zones may be linked with the component of extension parallel to the shear zones reducing the stress as well as the shallower position of the granitoid massif during the rifting of the Variscan continental crust (see Plašienka 2003a). The temperature values are not only the result of the geothermal gradient, but also of hydrothermal solutions activity and dynamometamorphic processes. In spite of this, it should be assumed that the value of the geothermal gradient ~20 °C/km accepted after Kováč et al. (1994) is too low, therefore the position of the granitoid massif of the Tatra Mountains assumed at ca. 10–11 km (200–225 °C) about 70–50 Ma ago seems to be too deep. The comparison of data relating to the temperature obtained from fission track geochronological dates by Kováč et al. (1994) as well as pressure and temperature obtained from fluid inclusions analyses, confirmed by the Cathelineau & Nieva (1985) and Cathelineau (1988) chlorite geothermometer, allows to estimate the geothermal gradient for the Late Cretaceous nappe folding at ca. 30 °C/km. Such high values of the geothermal gradient at that time could be connected with crustal heating due to the upwelling of the upper mantle at the base of the nearby Vahic ocean (Plašienka 2003b).

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